MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
SUMY STATE UNIVERSITY
UKRAINIAN FEDERATION OF INFORMATICS

PROCEEDINGS

OF THE V INTERNATIONAL SCIENTIFIC CONFERENCE

ADVANCED INFORMATION SYSTEMS AND TECHNOLOGIES

AIST-2017

(Sumy, May 17–19, 2017)

SUMY
SUMY STATE UNIVERSITY
2017

Comparison of the responsiveness of ultrasonic oscillating temperature sensors (UOTSes) and conventional sensors to temperature inflection points

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***Abstract* – Ultrasonic oscillating temperature sensors (UOTSes), in distinction to conventional temperature sensors, feature almost negligible settling time. This property can be useful for detecting malfunctions, failures and misuses of heat exchangers. However, most exchangers handle substantial thermal masses, which obscure the detection of any temperature changes.**

We compared the responsiveness of conventional DS18B20 sensors and an UOTS to the change in the temperature gradient of over 3.5 kg of water using a posteriori records. Temperature inflection points were estimated by extending the curves for separate distinct heating and cooling intervals that fit best and finding their interception. For the UOTS, the interception occurred about 100 seconds sooner, making it a potential candidate for detecting heat exchangers' irregularities.

Keywords – temperature sensing, ultrasonic oscillating temperature sensors, detecting temperature inflection points

I. INTRODUCTION

Sensing temperature is essential for the appropriate control of industrial processes in many industries (*e.g.*, in the food and petrochemical industries) and domestic appliances (*e.g.*, domestic heaters and refrigerators). The world market of temperature sensors was estimated to be worth over US $5 billion in 2016 [1]. Conventional sensors consist of an encased sensing element that needs to be brought to thermal equilibrium with the environment before taking any measurements. The typical settling times of these sensors are in the range of several seconds, which introduces unwelcome lag when monitoring processes of interest. By their very operating principle, conventional sensors sense temperature at a single point only. For this reason, many sensors need to be procured, installed, wired, serviced, and interrogated if the average temperature in a process vessel or industrial freezer is to be controlled or maintained.

In contrast, UOTSes sense temperatures based on the fact that the velocity of ultrasound depends upon the temperature in the medium of interest. This velocity ranges from hundreds of meters per second for gases to several kilometres per second for liquids and solids, making it possible to interrogate substantial ultrasound pathways at once with no settling time at all.

We are developing UOTSes that can be realised at a cost commensurate with the cost of conventional sensors (Table I, [2]).

TABLE I
PREVIOUS UOTS DEVELOPMENT

Refe-rence	UOTS center fre-quency	Approx i-mate sensiti-vity	Length of the path-way	Comments
[2]	330 kHz	280 Hz/K	0.03 m	Consistency of UOTS output frequencies vs. temperature at decreasing temperatures was reported
[3]	25 kHz	40 Hz/K	0.19 m	Different start up frequencies from the same UOTS in different experiments were observed
[4]	29 kHz	Tilt sensor	0.05 m	Reliable way to measure UOTS output frequency with any required resolution was presented
[5]	22 kHz	50 Hz/K	0.1 m	Implementation options for the electronic driver (including PSoC1*) were discussed
[6]	25 kHz	25 Hz/K	0.1 m	Comparison of ultrasonic thermometer architectures was conducted
[7]	46 kHz	60 Hz/K	0.1 m	Use of a UOTS for overnight measurements and observed hysteresis were reported
[8]	25 kHz	20 Hz/K	0.1 m	Simultaneous use of two UOTS for the same process, modular design of the electronic driver, and thermal hysteresis for the recorded data were discussed
[9]	27 kHz	30 Hz/K	0.1 m	Differential temperature measurement using two UOTS was reported

*PSoC1 refers to the programmable systems on chip series 1 device, which is a highly versatile electronic part manufactured by Cypress Semiconductor.

UOTSes consist of a pair of ultrasonic transducers placed inside a positive feedback loop (Fig.1).

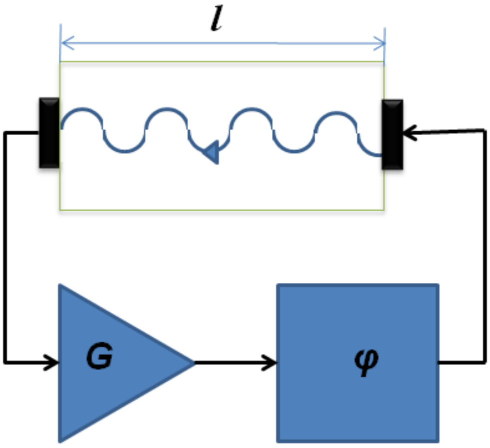

Fig.1. Block diagram of an UOTS

Practical temperature control of most heat exchangers is complicated by their substantial thermal mass. For this reason, a heater, after being switched off, will continue to heat the reservoir for some time until it reaches thermal equilibrium with the reservoir. Detecting the heater's failure is only possible after some time lag that might depend on the operating principle of the temperature sensors used.

In this paper, we compare the responsiveness of conventional DS18B20 sensors to a temperature inflection point to the responsiveness of an UOTS, assessed from *a posteriori* experimental data.

II. Experimental Setup and Procedure

The experiment was conducted by heating/cooling a plastic cylinder containing over 3.5 kg of water through air convection. This cylinder was equipped with six DS18B20 and one UOTS. First, the cylinder was placed into a thermal chamber with a heater that was turned on for a period of time (heating stage) and then was switched off (cooling stage). During the heating stage, the thermal chamber gained the same amount of energy over the same period of time, which should be possible to approximate by determining the linear dependence of the temperature versus time. At the second stage of the experiment, natural cooling should have obeyed Newton's law of cooling [11], and the chamber's temperature would be expected to exponentially decrease over time. After recording readings from all the sensors over the course of the experiment, we approximated these sensor readings separately for the heating and cooling stages by best fit curves. The interceptions of the best fit curves gave estimates for the temperature inflection points.

Fig. 2, left, presents the average temperature readings from the conventional sensors. The recorded output UOTS frequencies are plotted in Fig. 3, left. These frequencies were further processed to eliminate the intermittent deviations of the output frequency from the smooth, long-term curve as shown in the centre of Fig. 2.

III. Estimation of the Temperature Inflection Points Form the Recorded Data

Suitable heating and cooling intervals, where the readings of all the sensors changed steadily, were selected first. Because ultrasonic and temperature data were collected at different sampling rates, these intervals differ slightly as shown in the centre graphs of Fig.2 and Fig.3. These differences should not have notably affected the curves, as they are fitted over substantial time intervals. The parameters of the best fit curves for both the heating and cooling stages were independently calculated using the function **fit** of MATLAB.

The best fit interpolation curves for the average temperature were found to be linear (heating) and exponential (cooling) ones as expected. When plotted, these curves matched the corresponding average temperature curve segments well (Fig. 2, centre), and their extensions intersected at around t=2955 s (Fig. 2, right).

Approximating the UOTS output frequency curves required some additional considerations. An oscillator sustains steady state oscillations if it satisfies the Barkhausen criterion [12]: an UOTS must compensate for all the signal loop losses and provide zero end-to-end phase shift. The latter condition depends on the ultrasound TOF between the transducers (hence on the ultrasound velocity which depends on the temperature), making the UOTS feasible. Fig. 1 presents a block diagram for a UOTS, showing both the ultrasonic and electronic devices and the signal pathways relevant to the sensor's operation. The phase condition can be written as follows:

$$\frac{l}{\lambda} + , \qquad (1)$$

where λ is the ultrasound wavelength, , *c* is the ultrasound velocity, *l* is the distance between the ultrasonic transducers, *f* is the UOTS output frequency and is the overall phase shift in the positive feedback loop.

Assuming that, as the first order approximation, *G*, *l*, and are all independent of the ambient temperature and the UOTS output frequency, the wavelength of the standing wave between the transducers should remain unchanged, despite any changes in the ultrasound velocity caused by the temperature. Hence, if the velocity changed by due to some temperature change, the corresponding change in the UOTS frequency should satisfy the following relations:

$$\lambda = const \;\; => \;\; \frac{c + \Delta c}{f + \Delta f} = \frac{c}{f} \;\; => \;\; \frac{\Delta c}{c} = \frac{\Delta f}{f}$$

$$=> \quad \Delta f = \frac{\Delta c}{c} f \tag{2}$$

The derivative can be estimated by using either seminal Del Grosso and Mader fifth order polynomial approximation [13] or the considerably lighter limited applicability second order approximation proposed by Lubers and Graaff [14],

$$c(T) = 1404.3 + 4.7\,T^2, \tag{3}$$

where T is expressed in degrees Celsius.

The second order approximation seems appropriate here because of the temperature range of interest and the consideration of the electronic and mechanical components of the UOTS as being ideal. It follows that

$$\frac{d}{d'}$$

$$\Delta f = f \frac{4.7 - 0.08\,T}{1404.3 + 4.7\,T - 0.04\,T^2} \Delta T \; =>$$

$$\frac{\Delta T}{\Delta f} = \frac{1404.3}{f(} \tag{4}$$

Equation (4) stipulates that the UOTS output frequency depends on the temperature in a non-linear fashion, and the UOTS sensitivity depends on the ambient temperature and nominal UOTS operating frequency. Both of these conclusions were observed experimentally. The experimental UOTS output frequencies, recorded at the heating stage, were best approximated by a second order polynomial, while the output frequencies at the cooling states were best fit with an exponential curve. These curves intersected at around t = 2852 s (Fig. 3, right). Therefore, the UOTS data allowed for detecting the inflection point at approximately 100 s faster than the conventional sensor data *a posteriori*.

IV. Summary and Conclusions

Detecting heat exchanger irregularities can be complicated by the substantial thermal masses involved in the exchange process. We estimated the location of the detected temperature inflection points using *a posteriori* data recorded by both conventional temperature sensors and an UOTS. Suitable curves were fitted to distinct intervals of data related to the heating and cooling stages, and the curves' interceptions were used to locate the temperature inflections. The temperature inflection point, estimated from the conventional sensors' data, lagged by around 100 seconds compared to the point estimated from the UOTS data. This result supports the case for the application of UOTS for failure/malfunction/misuse detection in heat exchangers.

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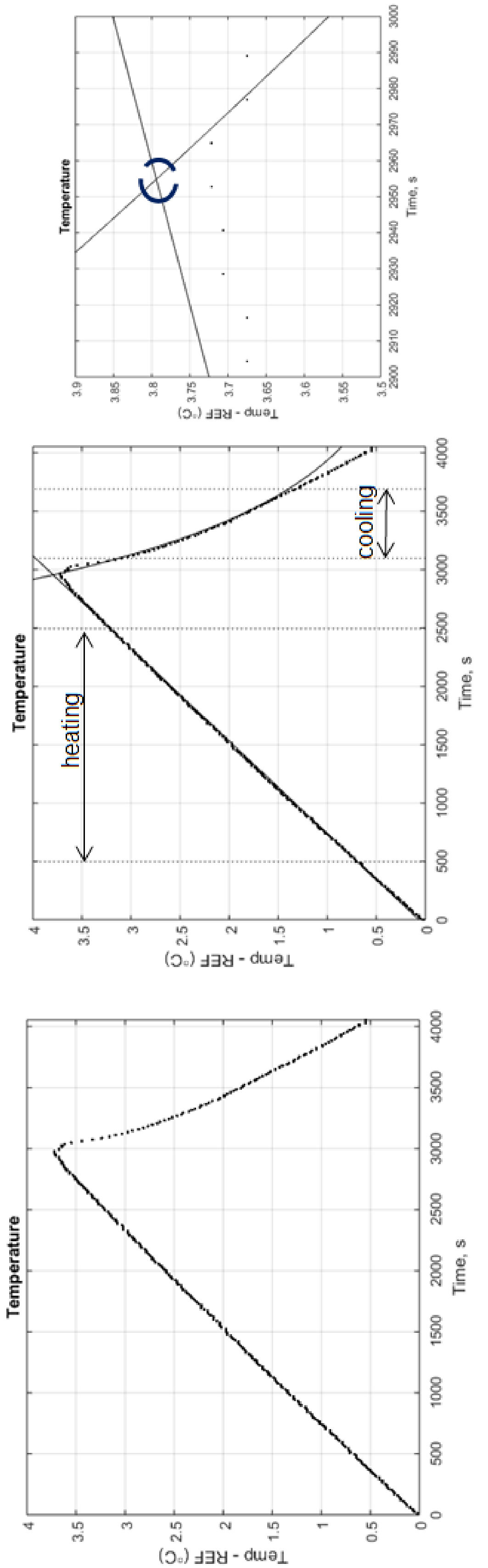

Fig.2. Average temperatures over the course of the experiment (left), with the heating and cooling stages shown (centre) and the estimate of the temperature inflection point (right) (REF=25.7°C)

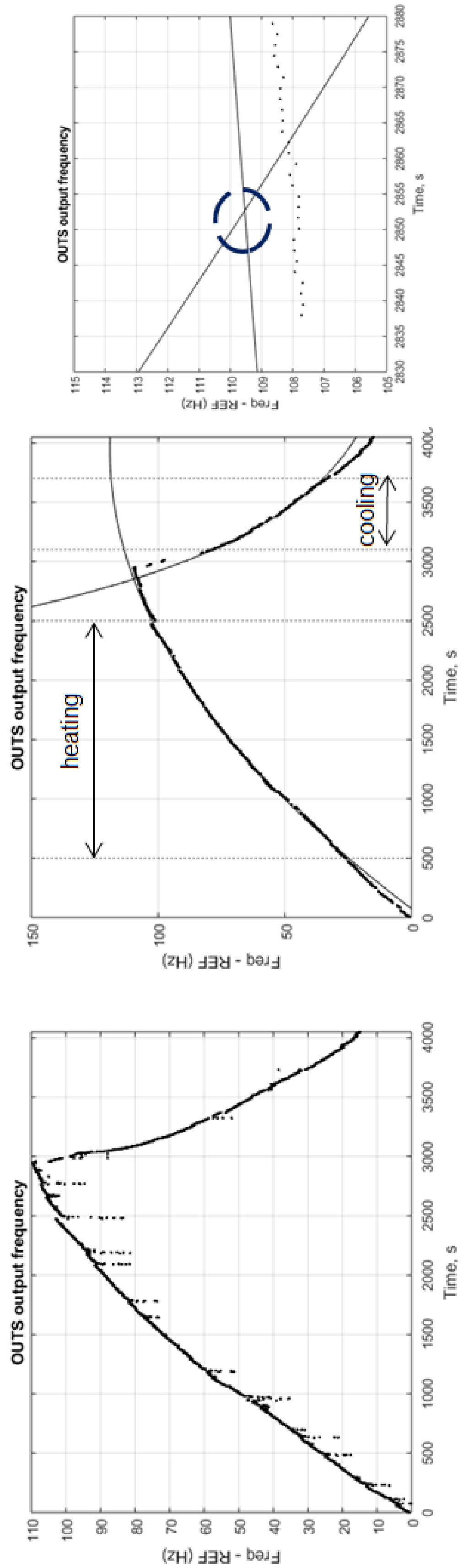

Fig.3. Recorded raw UOTS output frequencies (left), processed frequencies with the heating and cooling stages shown (centre) and the estimate of the temperature inflection point (right) (REF=27168 Hz)